

CFD ANALYSIS OF SLUDGE ACCUMULATION AND HYDRAULIC PERFORMANCE IN UCUBAMBA WSP (CUENCA, ECUADOR)

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ABSTRACT

The sludge management in Waste Stabilization Ponds (WSPs) is essential for safeguarding the system performance. Sludge accumulation patterns in WSPs are strongly influenced by pond hydrodynamics. CFD modeling was applied to study the relation between velocity profiles and sludge deposition during 10 years of operation of Ucubamba WSP in Cuenca, Ecuador. One tracer experiment was performed and three sludge accumulation scenarios based on bathymetric surveys were simulated. An RTD analysis illustrated the decrease of residence times due to sludge deposition. Sludge accumulation rates were calculated. The influence of flow pattern on the sludge deposition was studied, enabling better planning of future pond operation and desludging.

INTRODUCTION

Waste Stabilization Ponds (WSP) are typically applied for economical treatment of waste water in areas where vast stretches of land is available. The efficient and effective use of WSP systems is dependent on the safe and adequate management of their sludge (Nelson et al., 2004). Excessive sludge accumulation affects the hydraulic performance by reducing the effective volume, increasing short circuiting and feedback loads (Abis and Mara, 2005) and therefore reducing the treatment efficiency.

Past studies (Carre et al., 1990; Peña et al., 2000; Nelson et al., 2004; Abis and Mara, 2005; Picot et al., 2005) have measured and studied the sludge patterns and also evaluated the sludge production in some WSPs, reporting a wide range of per capita production from 0.021 to 0.148 m³ person⁻¹ yr⁻¹ (Mean Total Solids = 117 kg m⁻³). These studies emphasize that high temperatures enhance sludge degradation. However, more experimental data from different climates and pond configurations (inlet/outlet quantity and positioning) is needed to validate the sludge accumulation rates reported.

Sludge accumulation in WSPs is not evenly distributed throughout the pond domain. With regard to the sludge deposition patterns, Peña et al. (2000) states the strong influence of the geometry and the relative positioning of the inlets and outlets

in the sludge deposition patterns in two experimental anaerobic ponds in Colombia. Nelson et al. (2004) studied three full-scale facultative ponds in Mexico, and found that the maximum sludge accumulation occurred near the single inlet and also in some of the corners (dead zones). Abis and Mara (2005) and Picot et al. (2005) reported a similar behavior of sludge accumulation around the inlet area in three pilot scale ponds in UK and in 19 primary facultative ponds in France respectively. These studies certainly confirm that the presence of a single inlet favours the sludge accumulation in the nearby region but the reasons for such behaviour are not explained in any of the above studies. Sludge accumulation patterns in WSPs, therefore, are mainly influenced by the pond geometry and consequently by the hydrodynamic profile. A proper understanding of the complex pond hydrodynamics is a crucial for the sludge management in the pond systems.

Mathematical models have been used successfully in wastewater treatment systems for both system analysis and optimization. Since the introduction of CFD models to predict the flow patterns in ponds by Wood et al. (1995), the interest in CFD modeling for waste stabilization ponds expanded rapidly, particularly in practical applications. A relative large number of studies describe the usefulness of CFD models as a tool for assessing the system hydraulics (Wood et al., 1998; Peterson et al., 2000; Salter et al., 2000; Shilton, 2000; Vega et al., 2003; Karteris et al., 2005; Sweeney et al., 2005), and the biochemical transformation and degradation processes (Shilton and Harrison, 2003; Sweeney et al., 2007). These authors also state that CFD models are very useful in the design of new plants and the definition of operation rules improving the effectiveness of existing plants. However, according to Shilton et al. (2008) little scientific evidence exist regarding the validation of CFD models on full-scale systems. CFD studies of large full-scale WSPs systems are still to be properly reported in literature and, the study of sludge deposition pattern by means of CFD assessment has not been reported so far.

In view of the above discussion, the objectives of the research reported in this paper are threefold: (i) study the sludge accumulation rate and pattern over a period of 10 years in a large scale (13 ha)

facultative pond, (ii) evaluate the hydraulic efficiency of three different scenarios of sludge accumulation in the pond by means of RTD analysis, (iii) analyze the relationship between the flow profile in the pond and the sludge distribution pattern by means of 3D CFD modelling.

METHODOLOGY

The System

The Ucubamba WSP (Figure 1) is the biggest wastewater system in Ecuador. The system is in operation since 1999 by the Municipal Company ETAPA (*Empresa Pública Municipal de Telecomunicaciones, Agua Potable, Alcantarillado y Saneamiento de Cuenca, Ecuador*). The WSP system consists of a pre-treatment step (screen bars and grid chamber) followed by two parallel flow lines which comprise of an aerated pond (mechanical floating aerators), a facultative and a maturation pond. The WSP has a volume of 1 million m³ with a theoretical retention time of 11 days. The system treats mainly the domestic effluent of the Andean city of Cuenca - Ecuador, (2400 m a.s.l.; 400,000 inhabitants). The system is in operation since November 1999 and no sludge removal work has been executed to date. The original plan for desludging the system consisted of mechanical removal of the sludge every 5 years by emptying and drying one flow line at a time. However, once this period was accomplished, this plan was assessed to cause an organic overload in the remaining flow line for several months and have a detrimental effect on the receiving water body (Cuenca river). Consequently; a new strategy has been set based on an on-line "under water" sludge processing by dredging and dehydrating.

The present study is focused in the Facultative F1 pond where a full tracer experiment has been performed. The inlet/outlet of the Facultative F1 pond consists of a submerged pipe of 0.9 m diameter lying at the bottom of the 1.7 m deep pond and an overflow structure of 10 m length. The location of both structures is shown in Figure 1 (a), (b).

Tracer experiment

A tracer study was conducted in Facultative pond F1 during the driest season of the year 2010 to minimize the influence of rainfall on the variability of inflow effluent water. The tracer Rhodamine WT, considered non biodegradable nor absorptive in solids (Yanez, 1993), was mixed with pond water and added as a pulse in the channel upstream the inlet of the facultative pond in order to minimize the effect of thermal stratification. The fluorescence concentration in pond samples was measured using an AquafluorTM Fluorometer (<http://www.turnerdesigns.com>), a lightweight handheld instrument for fluorescence and turbidity measurements in-situ. The measuring device has a minimum detection limit of 0.4 ppb. Water samples were collected using an ISCO Automatic Sampler 6712 (<http://www.isco.com>). Sampling frequency was 5 minutes before the first peak of the tracer was observed, then gradually reduced to 60 minutes until 90% of the tracer was recovered, i.e. after 20 days. The samples were analyzed at the same temperature (18°C), using when necessary a thermal bath. The influence of natural fluorescence of algal biomass was controlled by measuring the background fluorescence concentration during several hours before the start of the test (Valero and Mara, 2009).

Sludge measurement

Five full bathymetries of the system were performed by ETAPA during 11 years of operation and analysis of the sludge composition was performed at a few locations. In this study, three bathymetries (the most equally spaced in time, performed in 2002, 2005 and 2009) are accounted for in the Facultative F1 pond. Figure 2 depicts the three sludge distribution scenarios based on bathymetry data. The bathymetries consisted in measuring the height of sludge with respect to the water level in 51 grid points within the pond domain. The points were chosen providing an even distribution in the pond, only assigning a denser grid in the region close to the inlet. A manual measurement technique was used to determine the sludge height at each grid location from an anchored boat. Using this procedure, only the consolidated sludge deposit was accounted (solids mass fraction > 13.3 %) which did not include the sludge in suspension (Durazno, 2009a).

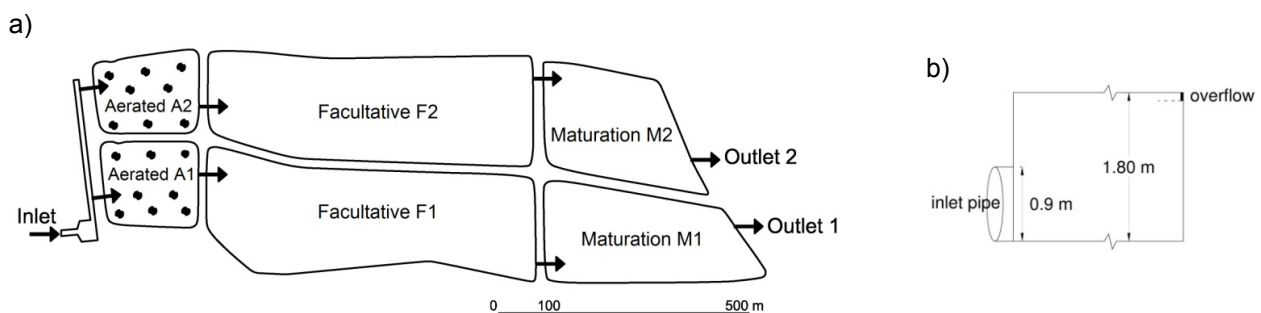


Figure 1: (a) Ground plan of the Ucubamba waste stabilization pond (WSP), Cuenca, Ecuador. (b) Side view of inlet/outlet location at the pond.

The three-dimensional surface profiles of the sludge distribution shown in Figure 2 were created directly from bathymetry data. A grid of 6m was created in each direction by the point kriging method (Cressie, 1991) with no smoothing post processing. The total sludge volume was calculated by integration using Simpson's interpolation rule to reconstruct the sludge surface. The per capita sludge production was calculated by dividing the sludge volume by the population served and the time of operation at each bathymetry. The sludge accumulation rates were calculated by dividing the sludge volume by the pond area and the time of operation

CFD Modelling

Three dimensional CFD simulations were performed for the facultative F1 pond using the

commercial software FLUENT v13 (ANSYS). Three different geometries/meshes were created corresponding to each sludge accumulation scenario. The presence of sludge was accounted for by removing the corresponding volume of the pond where sludge accumulation had been measured. A finite volume method was used for dividing the computational domain into 102,200 quadratic grid elements, representing the 13 ha facultative pond for scenario 1999 (no sludge accumulation). For subsequent scenarios the number of quadratic elements decreased respectively to 102,000 (2002); 98,900 (2005); and 88,200 (2009). For the unsteady CFD simulations, the fluid in the pond was assumed to be incompressible and exhibiting Newtonian fluid properties of water with a density of 998.2 kg m^{-3} and a dynamic viscosity of $1.003 \text{ E-3 kg m}^{-1} \text{ s}^{-1}$.

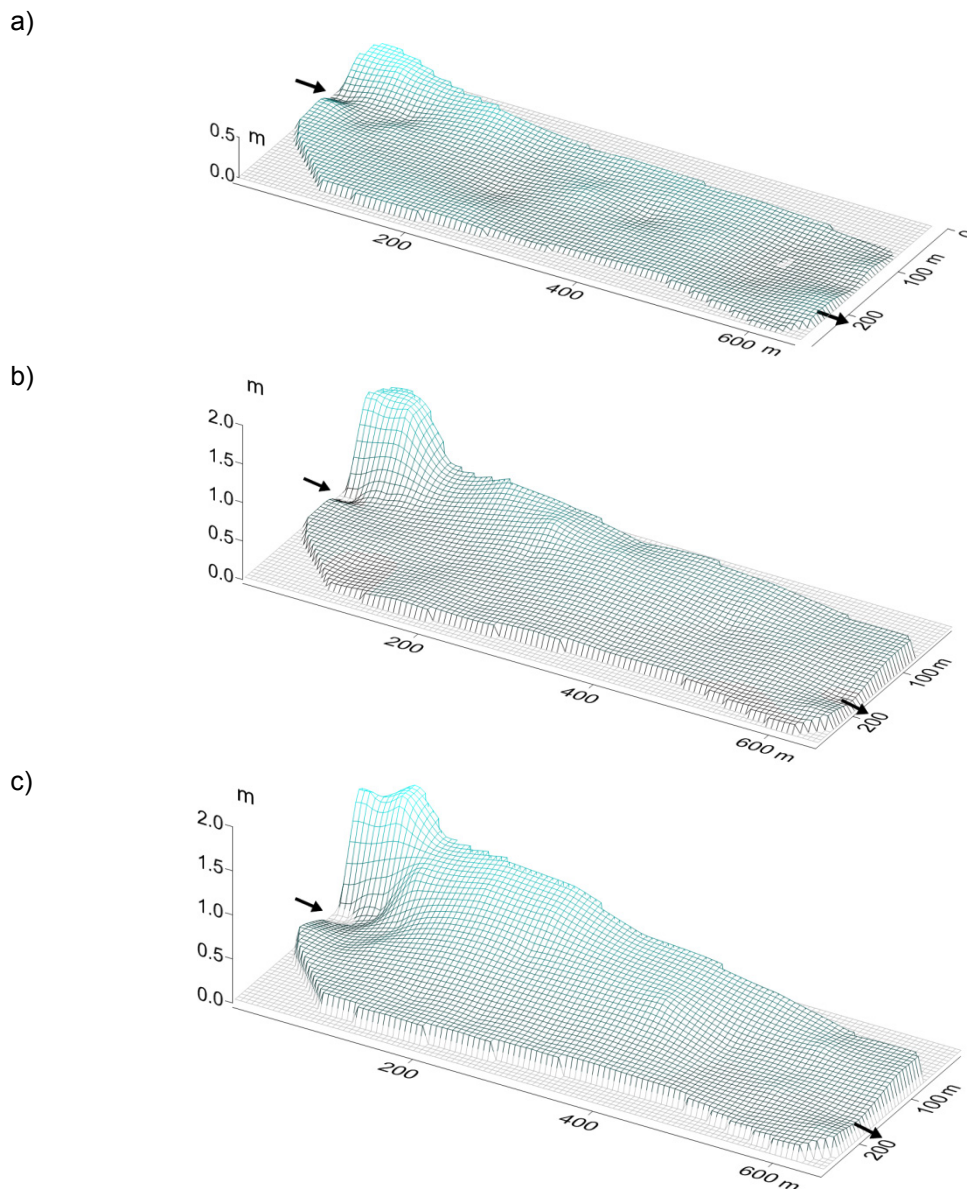


Figure 2: Sludge accumulation in Facultative F1 pond in the Ucubamba waste stabilization pond, corresponding to: a) March 2002, b) July 2005, c) February 2009 (note the difference in scale between the figures).

The concentration of suspended solids in the pond, in the order of 30 mg/l according to the system characterizations (Durazno, 2009b) is assumed not to affect these fluid properties. The turbulence was modelled using the standard k- ϵ model.

A constant velocity of 0.94 m/s was applied as boundary condition for the unsteady flow solution in the pond, while a transient inlet velocity profile (obtained from system operational records SCADA) was used for the tracer transport simulation, which accordingly calculates the inlet turbulent boundary condition. The effect of wind and temperature gradients has been neglected. The tracer residence time distribution (RTD) analysis (Levenspiel, 1999) was performed by imposing a transient simulation of tracer as a scalar on the velocity and turbulent fields obtained from the flow simulation. The dynamic advection of the tracer species, having identical properties as the fluid in the primary phase, has been considered for these simulations. The species transport model in Fluent v.13 was used for the determination of the RTD (Vedantam et al., 2006).

RESULTS AND DISCUSSION

Sludge accumulation rates

Table 1 shows the sludge accumulation rates obtained from the bathymetries in the Facultative F1 pond. The values of accumulation rates obtained are similar to those obtained in previous studies in Mexico, Brazil, Colombia, France (Nelson et al., 2004). However, it is stressed that the values reported in this article correspond to a secondary Facultative pond, where lower values of suspended solids and consequently lower values of sludge are expected compared to the primary Facultative and Anaerobic ponds reported in Nelson et al. (2004).

The accumulation rates in the pond (Table 1) tend to slightly increase over the years of operation. The latter could be explained by the decrease of treatment effectiveness due to the volume reduction and by hydrodynamic factors which will be addressed further. According to these calculated rates, and assuming they remain approximately constant, the sludge could reach up to 34% of the pond volume in 2012 (when the sludge removal is planned). Besides the influence on the hydraulic behaviour, the high depth sludge deposit in some regions of the pond has other implications for the system such as (1) presence of odour problems due to the anaerobic processes, (2) the growth of undesirable vegetation at the more shallow pond regions, (3) the presence of floating sludge masses (buoyed up by anaerobic gasses) that tend to accumulate in the corners by wind influence and (4) an aesthetic deterioration of the system observed in some locations.

Concerning full scale systems, the desludging operations have been economically studied by Picot et al. (2005) in 19 ponds in France concluding that “under water” desludging is around 50% more expensive than sludge removing after emptying the pond. However, it was stressed that local constraints definitely influence the choice of desludge procedure. In the particular case of Ucubamba, the pollution sensitivity of the receiving water body and the suitable site for punctual sludge disposal were among the factors for choosing the “under water” strategy. The good knowledge of the sludge deposition behavior is therefore crucial for the programming of the future activities in the system in this regard.

Tracer Experiment vs. CFD

Figure 3 shows comparison between the RTD curves obtained from the tracer experiment conducted in year 2010 and the CFD simulations corresponding to sludge accumulation patterns at the years 1999, 2002, 2005 and 2009. The behaviour of the CFD curve, as pointed out by Levenspiel (1999) is typically observed in vessels with strong recirculation pattern.

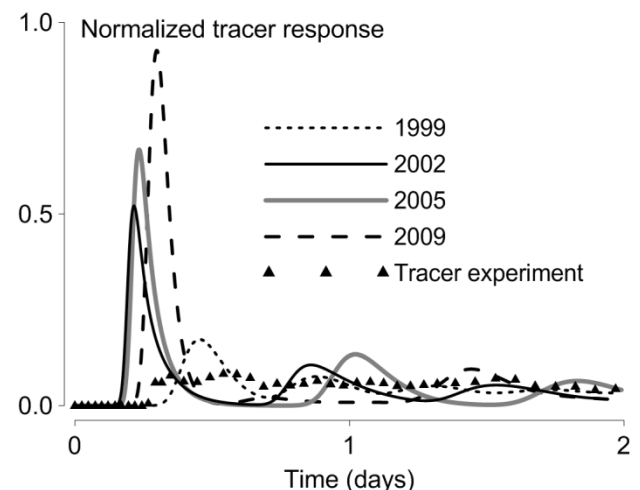


Figure 3. Concentration curves obtained in the CFD-RTD analysis of distinct sludge scenarios and in tracer experiment.

The RTD curve from the tracer experiment (corresponding to year 2010) is to some extent comparable with the CFD-RTD curve in the pond with no sludge accumulation (corresponding to year 1999). The CFD results are significantly affected by the approximated modeling of the sludge accumulation profiles consequently affecting the geometry of the pond. The internal geometry has a major impact on the RTD. The simplifying assumptions in the CFD model along with approximate geometry are the major reasons for the disagreement between the CFD and experimental results.

Table 1: Sludge accumulation figures in Facultative F1 pond

Bathymetry (operation period)	Sludge volume	Sludge volume / total volume	Sludge max thickness	Accumulation rates	
year	m ³	%	m	m ³ hab ⁻¹ year ⁻¹	mm yr ⁻¹
2002 (2.3)	10196	4.5	0.34	0.028	33
2005 (5.7)	29850	13.4	1.06	0.030	40
2009 (9.3)	50186	22.3	1.32	0.026	41

The peaks observed in the CFD results are not visible in the experimental results. However, the model behavior could be explained as follows. The reduction of volume in the region of the main dominant flow direction from inlet to outlet induces an increase of the velocity in that region and therefore the magnitude and occurrence in time of the peaks in the RTD curve. Although the match is not perfect over the entire RTD curve, the validation results of the CFD model are reasonable. A fine-tuning of the model and more accurate modeling of the sludge topology could improve the agreement. However, any further effort in this way should consider first the limitations and consequently the accurateness of the experimental data. On the basis of the match with the tracer results and considering the underlying assumptions, the authors concluded that the CFD model quite appropriately simulates the flow pattern of the WSP qualitatively.

RTD Analysis

Table 2 depicts the mean residence time obtained for each scenario of sludge accumulation. As expected, the mean residence times have decreased over the time of operation. The reduction is comparable to the respective volume reduction which has risen up to 27% in 11 years of operation.

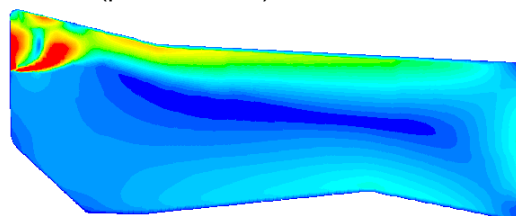
Table 2: Mean residence time (\bar{t}) obtained for each scenario of sludge accumulation.

	Scenario			
	1999	2002	2005	2009
\bar{t} (days)	2.94	2.50	2.32	2.05

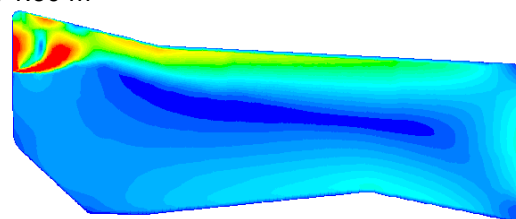
Liquid Flow Pattern by CFD

Figure 4 shows the liquid flow pattern obtained at different depths in the pond for the scenario 2005. This suggests a short circuit and a strong circular pattern of the tracer around the pond which is typical for this type of hydraulic systems without baffle structures (Shilton et al., 2008). Moreover, the influence of the inlet is particularly strong along the whole depth. It can also be noticed that the velocity distribution has no noticeable changes along the upper half of the pond (Figure 4 a, b and c). Finally, the presence of tiny dead zones near the inlet and a major dead zone in the centre of the pond are noteworthy.

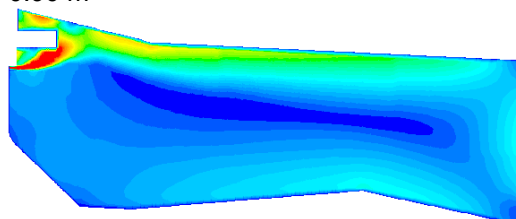
a) 1.80 m (pond surface)



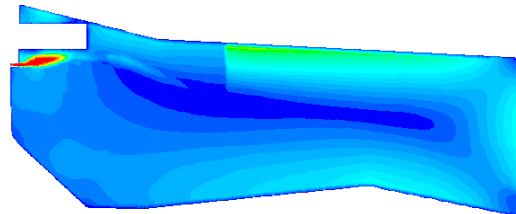
b) 1.30 m



c) 0.90 m



d) 0.50 m



e) 0.10 m



Figure 4. Comparison between velocity profiles at different depths from bottom of the F1 pond (scenario 2005).

CFD Sludge Accumulation Analysis

It was found that velocity distribution profiles did not change considerably despite the sludge accumulation, all exhibiting a circular flow pattern (Figure 5 a, b, c). The inter-dependence of flow pattern and sludge accumulation pattern is analyzed in Figure 5.

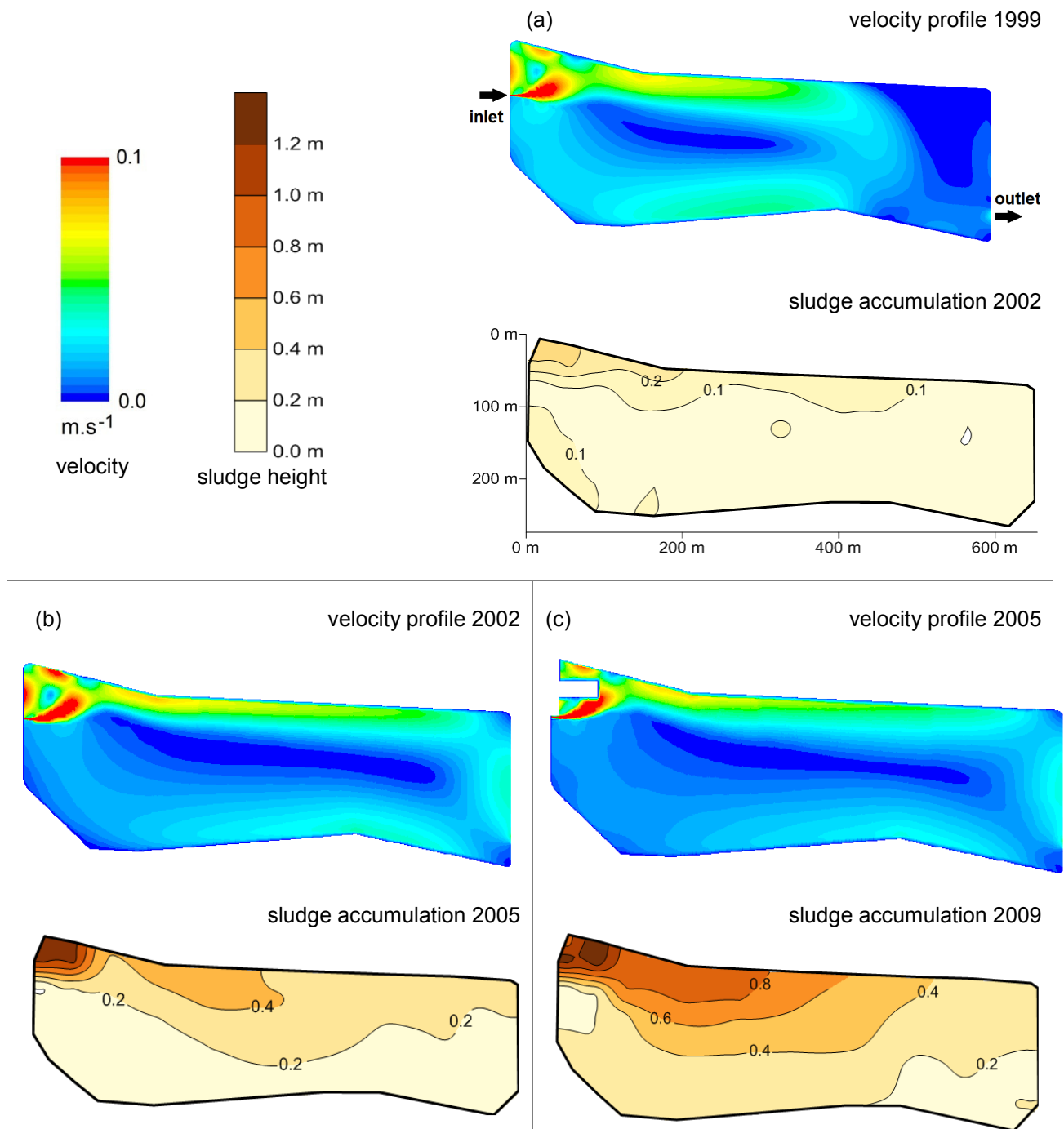


Figure 5. Comparison between velocity profiles (at mid depth) and sludge accumulation scenarios in Facultative F1 pond in the Ucubamba waste stabilization pond

As the sludge moves through the pond, the solids present in the sludge settle and accumulate. The settling pattern of the solids (viz. the settling velocities, directions and locations of settlement) is influenced by the sludge flow. As the sludge accumulates over time, it changes the internal topology of the pond and in turn affects the flow pattern.

Given the presence of only one small inlet pipe at one corner of a huge pond, it is obvious that a considerable sludge deposits are found near the inlet region. The maximum vertical liquid velocities

at the inlet region were in the range of 0.5 cm/s downward and almost zero in the rest of the pond. The solid particles are carried to some distance with the fast moving inlet liquid. Hence, these particles tend to settle down at some distance away from the inlet where the liquid velocities are low or zero. The downward velocities near the inlet further enhance the settling of solids. This behaviour is in agreement with previous studies, Nelson et al. (2004), Abis and Mara (2005) and Picot et al. (2005)

It is important to note the presence of vortex like structures with very low velocities, dead zones, in

this region. Most of the settling occurs in these dead zones giving rise to high sludge accumulations peaks. The presence of these sludge peaks near the inlet region can be seen in Figures 5, a, b and c. The sludge particles have a tendency to settle near the inlet zone (Schneider et al., 1983; Abis and Mara, 2005; Picot et al., 2005), but as the topology of the pond changes with time due to accumulation, the sludge is expected to start accumulating in the bigger central dead zone as well.

Figure 6 shows the velocity profile obtained in the CFD simulation of the sludge accumulation scenario of 2009. Based on the previous results and discussion, Figure 5 can be used to predict the future sludge accumulation profile where the sludge deposits will increase in the central zone and new sludge deposits could appear in the bottom left region of the pond.

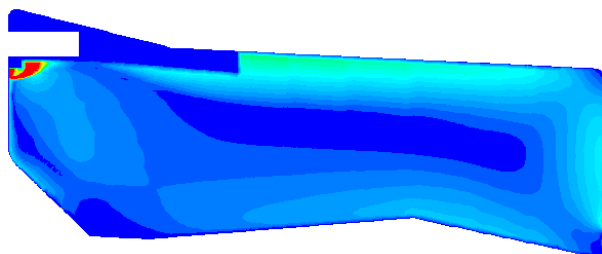


Figure 6. Velocity profile at mid-depth height of sludge accumulation scenario in 2009.

Since the sludge removal in the system will be an online process, the future topology of the sludge deposit will matter in this process. To favour the even distribution of the sludge, multiple inlets could certainly help, however the use of baffles can be a more economical option. The use of CFD models for testing the distinct effects of multiple inlets or presence of baffles will be definitively valuable, but needs further exploration, e.g. by explicitly modelling the sludge transport.

CONCLUSIONS

- The sludge accumulated in the Facultative F1 pond of the Ucubamba WSP showed a similar behaviour to other pond systems reported in literature with regard to the strong influence of the single inlet in the deposition pattern on the pond. The accumulation rates calculated from the bathymetric surveys are similar to the rates reported in previous studies.
- The CFD model has demonstrated its usefulness in the evaluation of the hydrodynamic performance of a system affected with large sludge accumulation and to analyze the sludge accumulation pattern in relation with the hydrodynamic footprint of the pond. It was shown that the RTD was affected. This will also lead to a different spatial model

definition when combined with a bioprocess model.

- A CFD model can potentially be used in the planning stage of a system for testing future scenarios of critical sludge accumulation and to prevent therefore the formation of uncontrolled anaerobic zones.

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